

## Preface

Traditional modulation methods adopted by space agencies for transmitting telecommand and telemetry data have incorporated subcarriers as a simple means of separating different data types as well ensuring no overlap between the radio frequency (RF) carrier and the modulated data's frequency spectra. Unfortunately, subcarrier modulation suffers from a number of disadvantages, namely, greater spacecraft complexity, additional losses in the modulation/demodulation process, and most important, at least from the standpoint of this monograph, a large, occupied bandwidth. One effort to mitigate the latter was to replace the more traditional square-wave subcarriers with sine-wave carriers, but this was not considered to be an acceptable solution for all space-exploration missions.

In the early digital communication years (i.e., 1960s and 1970s), bandwidth occupancy was really not an issue because of low data rates and the requirement for only a few data channels (subcarriers). Consequently, other attempts at limiting bandwidth occupancy were not considered at that time. As missions became more complex, however, the RF spectrum became more congested, and data rates continued to grow, thus requiring an attendant increase in subcarrier frequencies (equivalently, occupied bandwidth) and along with that, an increased susceptibility to interference from different spacecraft. A point came at which it was no longer feasible to use subcarrier-based modulation methods. Fortunately, during this same period, improved bandwidth-efficient modulation methods that directly modulated the carrier were being developed, which, along with improved data formatting methods (e.g., packet transfer frame telemetry) to handle the multiple channel separation problem, eliminated the need for subcarriers. Combining the packet telemetry format with any of the direct modulation methods and applying

additional spectral pulse shaping to the latter now made it possible to transmit messages at a high data rate while using a comparatively small bandwidth.

The purpose of this monograph is to define, describe, and then give the performance (power and bandwidth) of digital communication systems that incorporate a large variety of the bandwidth-efficient modulations referred to above. In addition to considering the ideal behavior of such systems, we shall also cover their performance in the presence of a number of practical (non-ideal) transmitter and receiver characteristics such as modulator and phase imbalance, imperfect carrier synchronization, and transmitter nonlinearity. With regard to the latter, the requirement of operating the transmitter at a high power efficiency, i.e., running the power amplifier in a saturated or near-saturated condition, implies that one employ a constant envelope modulation. This constraint restricts the type of modulations that can be considered, which in turn restricts the amount of spectral occupancy and power efficiency that can be achieved. Relaxing the constant envelope condition (which then allows for a more linear but less efficient transmitter power amplifier operation) potentially eases the restrictions on power and bandwidth efficiency to the extreme limit of Nyquist-type signaling, which, in theory, is strictly bandlimited and capable of achieving the maximum power efficiency. Because of this inherent trade-off between envelope (or more correctly, instantaneous amplitude) fluctuation of the modulation and the degree of power and bandwidth efficiency attainable, we have chosen to structure this monograph in a way that clearly reflects this issue. In particular, we start by discussing strictly constant envelope modulations and then, moving in the direction of more and more envelope fluctuation, end with a review of strictly bandlimited (Nyquist-type) signaling. Along the way, we consider a number of quasi-constant envelope modulations that have gained considerable notoriety in recent years and represent a good balance among the above-mentioned power and bandwidth trade-off considerations.

Finally, it should be mentioned that although the monograph attempts to cover a large body of the published literature in this area, the real focus is on the research and the results obtained at the Jet Propulsion Laboratory (JPL). As such, we do not offer this document to the readership as an all-inclusive treatise on the subject of bandwidth-efficient modulations but rather one that, as the title reflects, highlights the many technical contributions performed under NASA-funded tasks pertaining to the development and design of deep-space communications systems. When taken in this context, we hope that, in addition to being informative, this document will serve as an inspiration to future engineers to continue the fine work that was initiated at JPL and has been reported on herein.

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